e/m APPARATUS FOR LABORATORY USE IN THE PHYSICAL SCIENCES

A Thesis

Presented to

The Graduate Division

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In Partial Fulfillment

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Master of Arts in Physical Science

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by

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CHAPTER I

INTRODUCTION

Purpose. The purpose of this investigation was to develop an apparatus to demonstrate the effect of an electric and magnetic field on an electron beam and to measure the ratio of the charge of an electron to its mass by using balanced electric and magnetic fields.

Historical background. In a second semester course in physics, the student is asked to determine the ratio of charge of an electron to its mass. In many laboratories this experiment is omitted or sometimes performed by only a few of the students because of the high cost of the commercial apparatus.

The Physics Department at Drake University wanted an apparatus built at a minimum cost from existing surplus cathode ray tubes and other electrical supplies that could be used to show the effects of an electric and magnetic field on an electron beam and also be used to make a determination of the ratio of the charge of an electron to its mass.

A review of the literature indicated that there are three major types of apparatus that have been used to determine the charge to mass ratio of an electron. They are:

The J. J. Thomson Method; The Lenard Method; and the Busch Method.[1]

The J. J. Thomson Method was the first used to determine the ratio of charge to mass of an electron. It consists of a cathode ray tube with internal deflection plates and an external magnetic field placed perpendicular to the neck of the tube in the region of the deflection plates. A stream of electrons is accelerated from the cathode through the plate to the screen by a large potential between the cathode and plate. While traveling from the cathode to the screen the electron beam is passed through the region of the magnetic field which deflects the beam into a circular path due to the force of the magnetic field on the beam. It is this force that constitutes the centripetal force to the electron beam. The magnetic field intensity can be calculated from the magnitude of the current used in the coil and the dimensions of the coil.

In order to determine the velocity of the electrons, Thomson applied the necessary electrostatic potential to the internal deflection plates so that the electrons were deflected back to the center of the screen where they had been observed before the magnetic field was applied. The velocity

[1] J. Barton Hoag, and S. A. Korff, Electron and Nuclear Physics (New York: D. Van Nostrand Company, Inc., 1948), pp. 21-35.

can be calculated when the magnitude of the electrostatic force is equal to the magnitude of the magnetic force.

In this pioneering work, Thomson obtained a value for e/m of 7.7×10^6 e.m.u./gram which was of the order of magnitude of the now accepted value of 1.76×10^7 e.m.u./gram.

The Lenard Method is very much the same as the Thomson Method except that Lenard applied the magnetic field over the entire path of the electrons, that is the entire cathode ray tube was placed in the magnetic field.

The Busch or Helical Method uses a cathode ray tube but places it inside of a solenoid. An alternating potential is applied across the deflection plates and serves to sweep the electron beam back and forth. A line instead of a spot is then observed on the fluorescent screen. The electrons travel in parabolic paths as they pass between the deflection plates, after which they travel in a straight line to the screen. A magnetic field is applied so that the lines of force are parallel to the axis of the tube. This field does not affect the forward motion of the electrons but does act on the transverse motion. This causes the electrons to be deflected into circular paths at right angles to the axis of the tube at the same time that they are traveling down the tube. The resultant of the combined circular and linear motions is such that the electrons travel in helical paths down the tube.

The magnetic field is adjusted until the time for the electrons to make one circular revolution is equal to the time taken for them to travel forward from the deflection plates to the screen. This condition can be detected by observing the line on the screen. As the magnetic field is increased from zero, the line shortens and rotates until, at a critical magnetic field strength it is reduced to a small spot on the screen. The ratio of charge to mass can be calculated when this condition is satisfied.

In all of the methods just described, there are four basic conditions that relate (1) the centripetal to magnetic force, (2) the magnetic force to the electric deflecting force, (3) the velocity of the electrons to their accelerating potential and (4) the velocity to the frequency of an oscillator. There are some forty-three different methods for determining e/m using these relationships.[1]

The methods mentioned above are those actually used in early work to determine and confirm the ratio of charge to mass of an electron. So far nothing has been said about methods or apparatus that has been devised for use in the introductory Physics Laboratory. Most methods that have been used for this purpose have been modifications of the three main methods described before.

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[1] Ibid., p. 29.

A. H. Weber and J. F. McGee, of St. Joseph's College, designed an apparatus to determine e/m. Their apparatus used an oscillograph with the tube removed and reconnected to the original socket so that the tube would be external to its original placement. Helmholtz coils were placed in such a position that the magnetic field covered the area from the deflection plates to the screen. Balanced electric and magnetic fields were used and e/m calculated by measuring the deflection due to the electric field and placing this in a complicated double integral formula.[1]

McCombs and Pietenpol designed a simple and inexpensive apparatus for determining e/m by using the Busch method. They used a 3HP7 cathode ray tube and placed it inside of a solenoid consisting of 689 turns of wire, 76.8 centimeters long and 14.1 centimeters in diameter. They arrived at results with about two per cent error from the accepted value.[2]

Bradley, of Western Michigan College, made an apparatus for determining e/m of an electron. He also used

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[1]A. H. Weber, and J.F. McGee, "The Specific Charge of the Electron by the Thomson Method with a Commercial Cathode Ray Oscillograph," The American Journal of Physics, VII (February, 1939), 62-64.

[2]Rollin K. McCombs, and William B. Pietenpol, "An Inexpensive Arrangement for Determining e/m by Busch's Method," The American Journal of Physics, XVII (February, 1949), 78-79.

the Busch method. He applied an A.C. deflection voltage of 60 volts to one set of plates of a 902A cathode ray tube and connected the other set together to ground. The A.C. voltage produced a line on the screen of the tube. As the current in the solenoid increases, the line appears to rotate and to shorten. When exactly a whole number of helical turns are made by the electron stream, the line will appear as a dot and e/m can be calculated.[1]

Miller used a modified Busch method to determine e/m in the physics laboratory. He modified the Busch method by substituting an alternating current in the solenoid and simultaneously applying to the deflection plates a voltage which was proportional to the solenoid current. As a result, all electrons move in spirals of the same radius and the pattern observed is a portion of a circle. By adjusting the magnetic field until a full circle just appears, e/m may be calculated.

By means of the Classen method, which is very much like the Lenard and also very much like a Dempster Mass

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[1]George Bradley, "Measurement of Electronic Charge-to-Mass Ratio for the General Physics Laboratory," The American Journal of Physics, XXIV (May, 1956), 410-411.

[2]Bernard J. Miller, "Modified Helical Method for Determining e/m," The American Journal of Physics, XXVII (April, 1959), 256-259.

Spectrograph, Blair and Likely, of the University of Minnesota, built an apparatus for the physics laboratory that could be used to determine e/m for electrons. Their apparatus consisted of a flanged metal vacuum chamber that contained the electrode system, a filament, two adjustable slits, and a collector. Helmholtz coils supplying the magnetic field were mounted externally. Acceleration potentials of 750-1500 volts, and magnetic fields of 60-70 gauss are required. The electrode system can be conveniently removed from the chamber for inspection and measurement. They arrived at values of e/m within two per cent of the accepted value.[1]

All of the methods mentioned above used either the Busch or the Lenard methods. It is felt that the average physics student would not have the proper background to handle the mathematics involved in solving the equations for the path of a helical beam or the background to understand the principles of the combined motions of the electron due to the changing electric and magnetic fields. By devising an apparatus using the Thomson method, the student would be able to see and understand the principles involved in an e/m experiment.

This research involves the construction of such a

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[1]Robert G. Marcley, "Classen's Method for e/m of Electrons Apparatus," The American Journal of Physics, XXIX (January, 1961), 26-29.

Thomson apparatus so that the cost could be kept to a minimum and also simple enough that the student does not get lost in the manipulation of the apparatus and the mathematics of the experiment. The construction of such an apparatus involved the building of a high-voltage power supply, the various controls needed to adjust the voltage on the deflection plates and the construction and calibration of solenoids to produce the magnetic fields.

CHAPTER II

CONSTRUCTION AND MATERIALS

The e/m apparatus contains five major parts which are: (1) The power supply, (2) The cathode ray tube, (3) The deflection and focus controls, (4) The magnetic field coils and (5) The controlling circuit for the magnetic field coils. This chapter is devoted to the construction and function of each of the five major parts and the operation of the final assembled apparatus.

Power supply. The power supply consists of a simple half-wave rectifier using a 6AU4 half-wave rectifier tube and a ripple filter. The voltage transformer has a high voltage secondary of 350-0-350 volts and a 6-volt filament section. This transformer is nearly the same type that was used in the earlier television sets.

The ripple filter is a choke input type.[1] The capacitor is rated at .1 mfd and 5000 volts D.C. and was purchased from surplus.

This power supply has an output of about 1000 volts D.C. with a load of 5 ma., which is more than sufficient to

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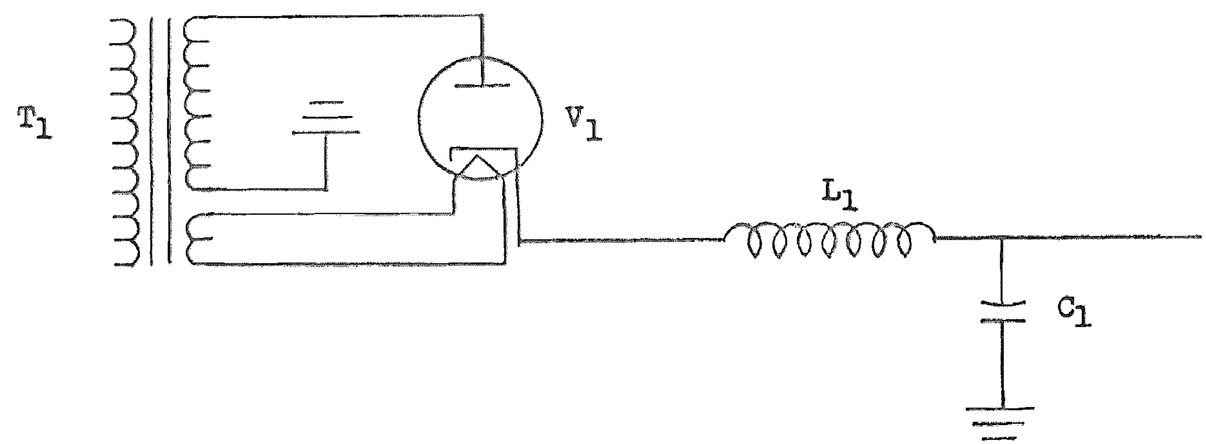
[1]Alex Romanowitz, Fundamentals of Semiconductor and Tube Electronics (New York: Wiley and Sons, Inc., 1963), p. 158.

supply the necessary voltage to the cathode ray tube for acceleration of the electrons and for focus of the electron beam. The power supply also furnishes the filament voltage to the cathode ray tube. The circuit of the power supply is shown in Figure 1.

Cathode ray tube. The tube used was a 5BP1 cathode ray tube with two pairs of deflection plates, an accelerating anode and a focusing anode. This tube requires 6 volts for the filament, 1000 volts for acceleration of the electron beam and 400 volts for focusing. The tube is about 13 centimeters in diameter at the face and about 43 centimeters long.

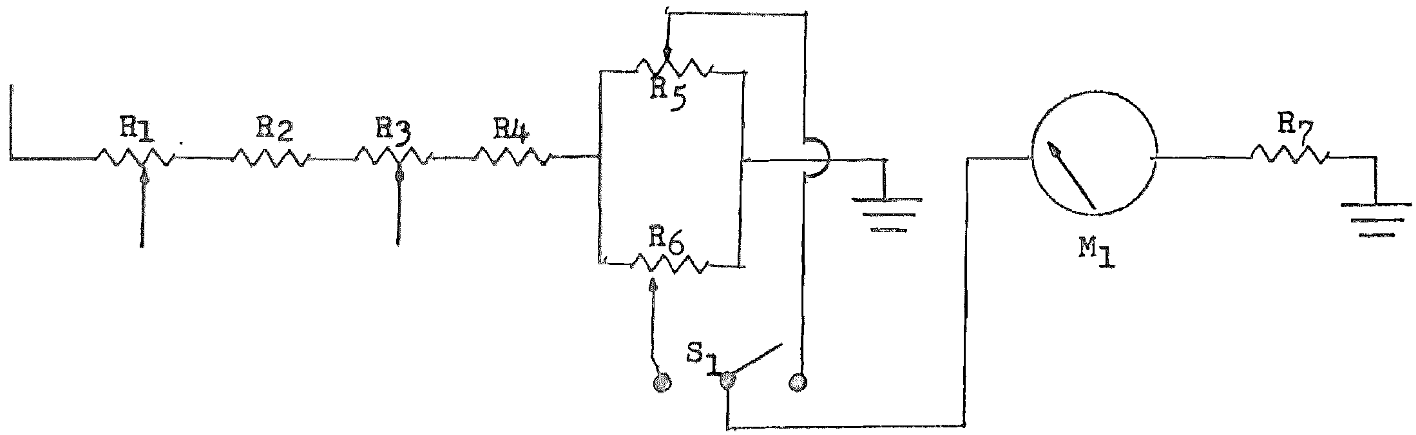
It is the function of the cathode ray tube to produce a beam of electrons, indicate the position of the beam by producing a bright spot on a florescent screen and to house the focusing anode and the deflection plates.

Deflection and focus controls. The deflection and focus voltages are produced from a simple voltage divider system. The circuit of the voltage divider system is shown in Figure 2. The intensity control is a one hundred thousand ohm variable resistor in this divider system and the focus control is a five hundred thousand ohm variable resistor. The vertical and horizontal deflection controls are also five hundred thousand ohm variable resistors connected



T_1 = Power Transformer; 350-0-350 volt secondary with 6 volt filament section.
V_1 = 6AU4 half-wave rectifier tube.
L_1 = Value not known.
C_1 = 0.1 mfd. rated at 5000 VDC.

Figure 1. Power Supply Circuit



R_1 = 100K Ohms.

R_2 = 120K Ohms.

R_3, R_5 and R_6 = 500K Ohms.

R_4 = 560K Ohms.

R_7 = 2 Meg. Ohms.

M_1 = 0-100 Volt Voltmeter

S_1 = Single Pole Double Throw Switch

Figure 2. Deflection and Focus Control Circuit

in parallel in the divider system. A single pole double throw switch permits both vertical and horizontal deflection voltages to be measured with a single voltmeter.

This system provides the proper focus, intensity and deflection voltages as well as providing a method to measure the magnitude of the deflection voltage.

Magnetic field coils. The selection and construction of the magnetic field coils proved to be a major problem of this research. It was decided that either Helmholtz Coils or a pair of solenoids would be used because of the simplicity of construction. Helmholtz Coils are two circular coils of equal diameter, equal number of turns of the same size wire and separated by a distance equal to the radius of the coils. Solenoids are considered to be coils which are longer than their radius. For this work the radius should be small compared to the length so the magnetic field will be very nearly uniform throughout the entire length of the solenoid.

The first set of coils to be constructed were Helmholtz Coils with a diameter of eight centimeters. This diameter was chosen because the neck of the cathode ray tube was four centimeters in diameter and the distance between the coils must be equal to the radius of the coil, thus the diameter had to be eight centimeters or more. Preliminary investigation indicated that these coils would not be satisfactory because the magnetic field produced by them was not uniform throughout its entire diameter. This causes the electron beam to be curved by a nonuniform amount as it passes through the magnetic field.

It was then decided to try using two long solenoids separated by four centimeters so that they could be placed perpendicular to the deflection plates. The first set of solenoids constructed were about twenty eight centimeters long and four centimeters in diameter. These coils were constructed on a power lathe by winding twelve hundred turns of number twenty-six copper enameled wire on a cardboard mailing tube.

Again preliminary investigation indicated that these coils were not exactly suitable either because of two factors. First, it was not possible to arrive at a value for the magnetic field strength in the gap that agreed with values derived by calculations from a formula. Second, the magnetic field covered too much area in the region of the deflection plates. This meant that the electron beam was subjected to a magnetic field for twice the distance that it would be subjected to an electric field. In order to use an electric field to balance the effect of the magnetic field both the electric and magnetic fields must be nearly co-extensive in the tube.

The work with the four-centimeter solenoid indicated that this might prove to be the most satisfactory type coil to produce the magnetic field but a new and smaller solenoid would have to be built and tested.

The new set of solenoids that were built were two and one half centimeters in diameter and twenty eight centimeters loing. These coils each consisted of twenty-four hundred turns of number twenty-six copper enameled wire. These were mounted end to end with a four-centimeter gap and placed perpendicular to the neck of the cathode ray tube in the region of the deflection plates. The results produced with this set of solenoids proved to be very good and it was decided to use this set in the final apparatus.

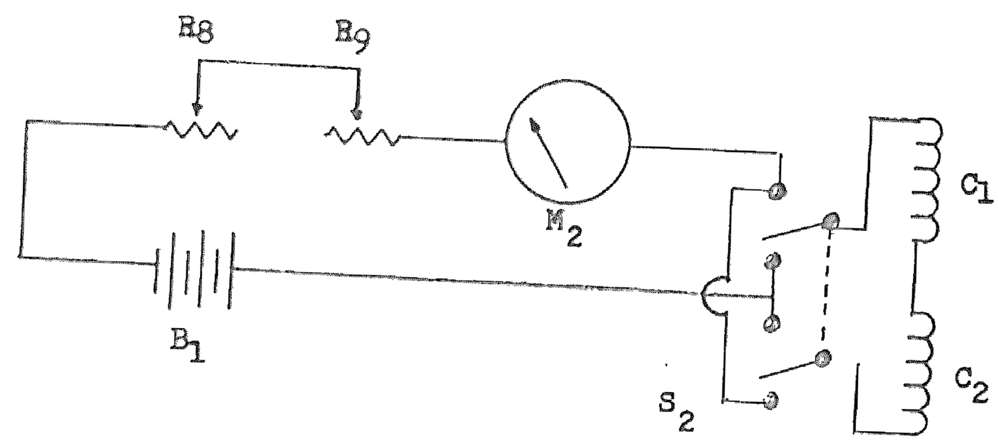
<u>Controlling circuit for the magnetic field</u>. The controlling circuit for the magnetic field consists of a double pole double throw switch, a milliammeter and two variable resistors. The variable resistors serve to control the current through the coils. One of the variable resistors is a one hundred ohm resistor for coarse adjustment and the other is a fifty ohm resistor for fine adjustment. The milliammeter is a fifty microampere basic movement with a proper shunt so that the meter will read 0-400 milliamperes. The double pole double throw switch is used to reverse the direction of the current flow in the coil and thus reverse

the direction of the magnetic field. The circuit for the magnetic field is shown in Figure 3.

The function of this circuit is to control the current in the solenoids, thus providing magnetic fields of various intensities.

Assembled apparatus. The cathode ray tube is mounted horizontally about thirty-two centimeters above the base of the apparatus. The face of the tube protrudes through a twelve centimeter hole in a twenty-six centimeter by fifty centimeter aluminum front plate of the apparatus. The voltmeter for measuring the deflection voltages and an ammeter for measuring the solenoid current are mounted directly below the cathode ray tube face on the front panel. The resistors and switches for the deflection, focus and magnetic field control circuits are mounted below the meters. Power is fed to the base of the cathode ray tube by means of a thirteen prong socket which is mounted on an aluminum support, ten centimeters by thirty centimeters, at the rear of the apparatus.

The power supply must be kept separate because the magnetic field of the transformer interferes with the electron beam in the tube when it is near. Therefore, the power supply is placed about two meters from the cathode ray tube assembly, and power furnished from the power supply to the apparatus by means of a power cord.



R_8 = 100 Ohm Variable Resistor.

R_9 = 50 Ohm Variable Resistor.

M_1 = 0-400 ma. Milliammeter.

B_1 = Six 6 Volt Batteries.

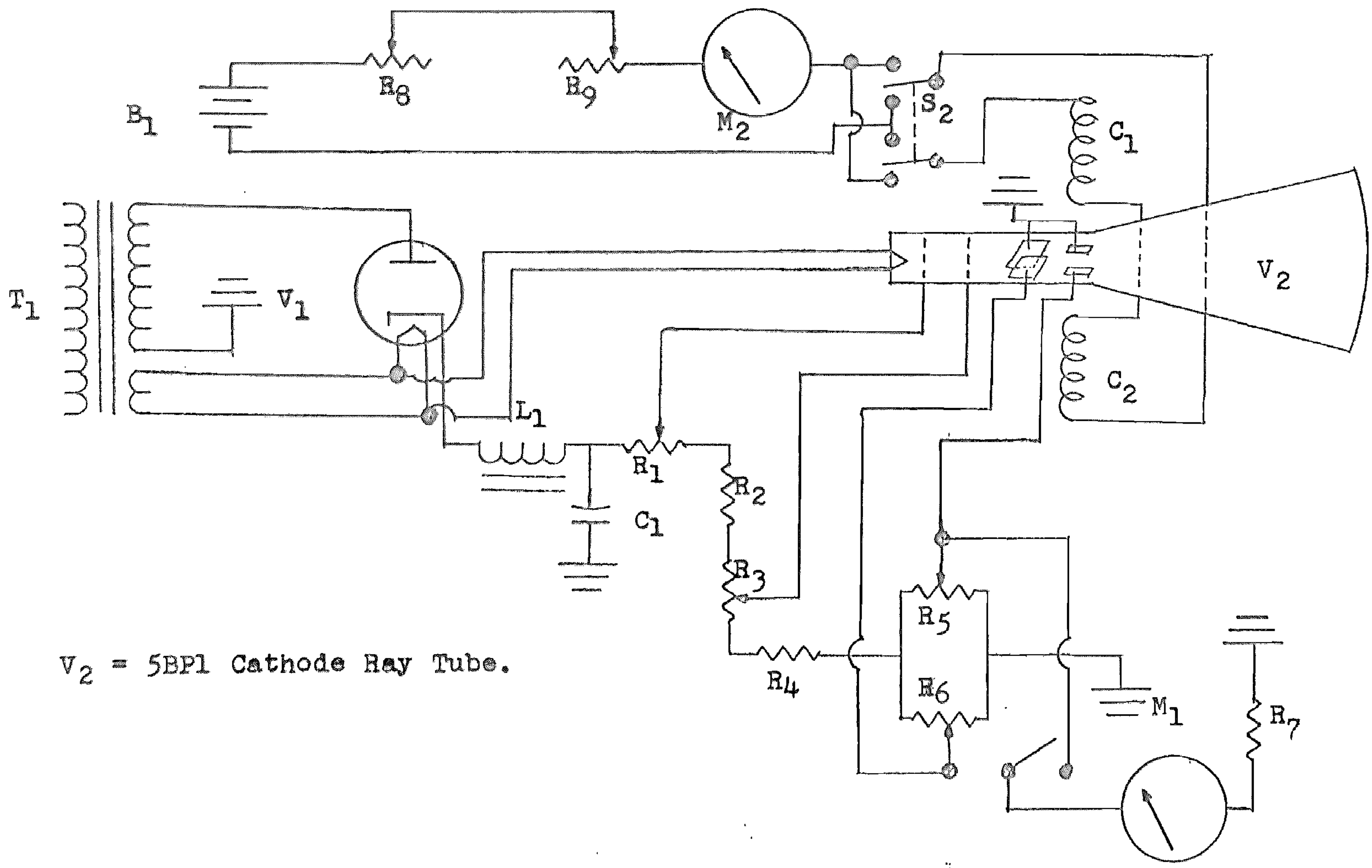
C_1 and C_2 = 2400 Turn Solenoids.

S_1 = Double Pole Double Throw Switch.

Figure 3. Controling Circuit for the Magnetic Field.

The magnetic field coils are solidly mounted perpendicular to the neck of the cathode ray tube and fourteen centimeters from its base. Current for the magnetic field is supplied by six 6-volt batteries mounted directly behind the front panel.

The circuit of the assembled apparatus is shown in Figure 4. The final assembled apparatus is pictured in Figures 5 and 6.



V_2 = 5BP1 Cathode Ray Tube.

Figure 4. Complete Circuit Diagram.

Figure 5. Front View of Apparatus

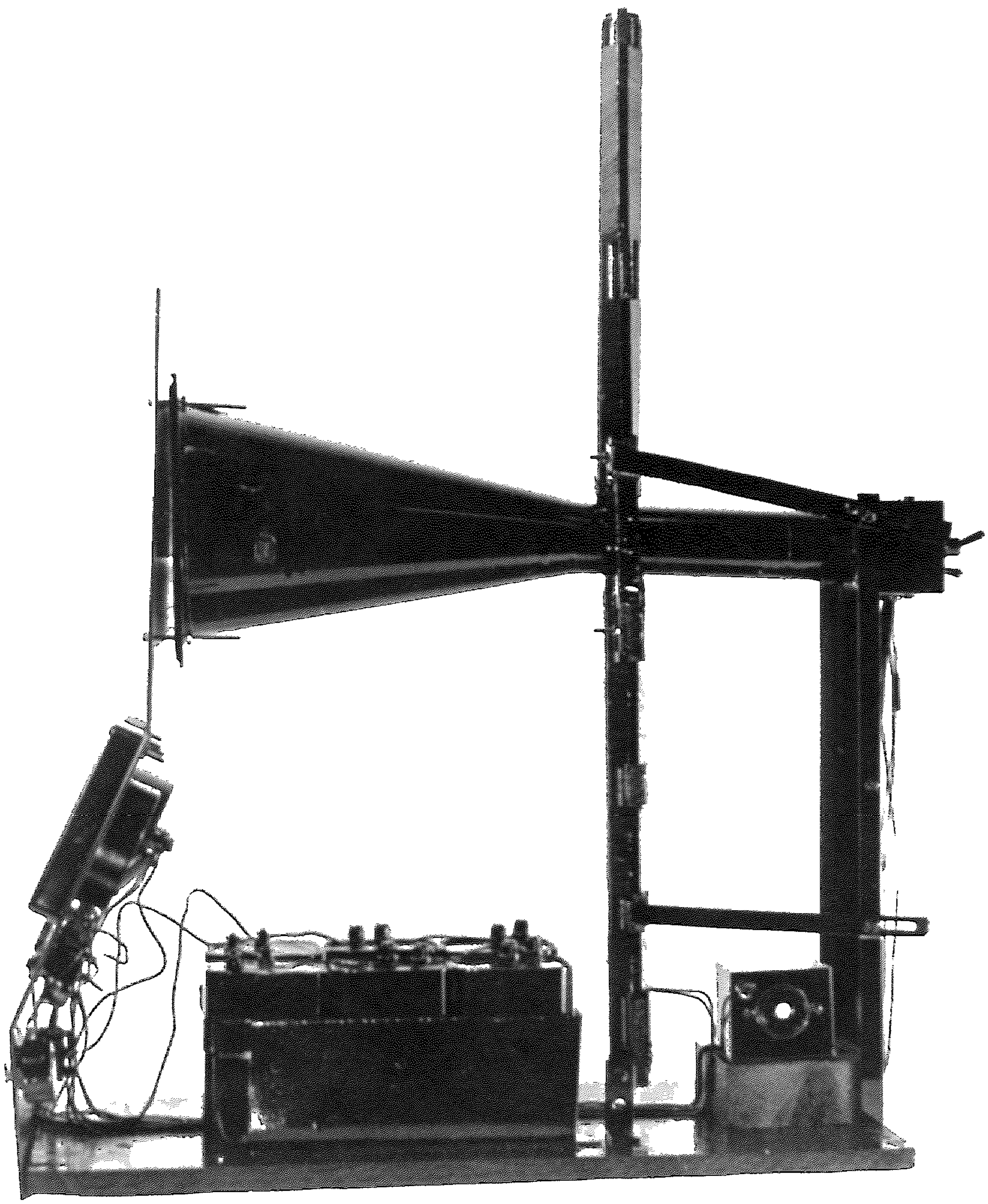


Figure 6. Side View of Apparatus

CHAPTER III

THEORY

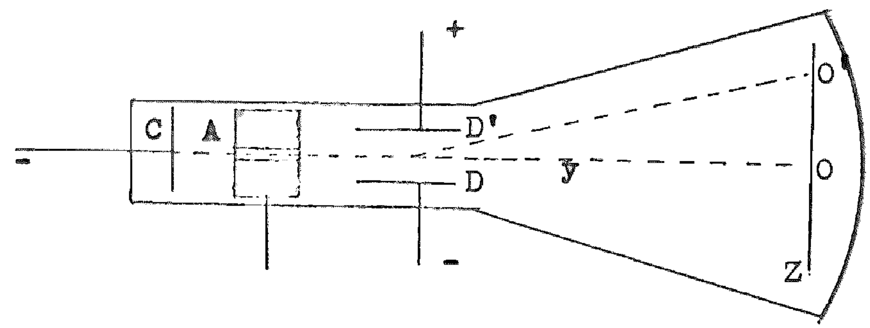
Theory of operation. The cathode ray tube, shown in Figure 7, consists of a cathode, an anode with a small hole in the center of it, a pair of deflection plates, and a fluorescent screen. Electrons are accelerated from the cathode to the anode. While most of the electrons strike the plate, some pass through the small hole and proceed with uniform velocity v until they pass between the deflection plates and strike the screen at O, producing a bright spot.

If a voltage V is applied between the deflection plates then the electrons will be deflected upward by a force, F, given by

$$F = \frac{Ve}{d} = ma$$

where e is the charge on the electron, m is the mass of the electron, d the distance between the deflection plates and a the acceleration of the electrons.

Since the electric field is uniform between the plates, the path of the electrons will be parabolic. After they leave the region of the deflection plates, they will travel in a straight line and strike the screen at point .



C = Cathode.

A = Anode.

D and D' = Deflection Plates.

Z = Fluorescent Screen

y = Electron Beam Deflection at end of Deflection Plates.

O = Center of Screen

O' = Position of Electron Beam

Figure 7. A Typical Cathode Ray Tube

Rearranging the terms in the previous equation an expression for e/m is given by

$$e/m = \frac{ad}{V}$$

To determine e/m, the acceleration must be measured. This can be done by knowing that the amount of deflection, y, parallel to the electric field between the plates is given by

$$y = \tfrac{1}{2}at^2$$

where t is the time during which the electron is being accelerated and is given by

$$t = \frac{x}{v}$$

where x is the length of the deflection plates.

Solving the above two equations for the acceleration, a, of the electrons, the expression for the acceleration becomes thus

$$a = \frac{2yv^2}{x^2}$$

The velocity v can be found with the aid of a magnetic field applied at right angles to the electric field and acting over the same length of path, x. If the strength of the magnetic field is B, the electron will experience an additional force, F', given by

$$F' = Bev$$

The magnetic field is set so that the deflection of the electrons due to the magnetic field will be downward. This field can be adjusted so that the electron beam will be returned to its no-fields path, as observed by the return of the fluorescent spot to point O. When this occurs the force due to the electric field is equal to the force due to the magnetic field. Thus

$$\frac{Ve}{d} = Bev$$

from which

$$v = \frac{V}{dB}$$

Combining this equation with the first equation on page 24 and the last equation on page 24, the expression for e/m becomes

$$e/m = \frac{2Vy}{dB^2x^2}$$

If V and B are expressed in abvolts and gauss respectively and the other units in the cgs system, the value for e/m will have units of e.m.u./gram.

The amount of deflection, y, parallel to the electric field at the end of the deflection plates can be found by knowing the distance, S, from the center of the plates to the screen and the amount of deflection, Y, of the bright spot on the screen and the length x of the plates thus

$$y = \frac{Yx}{2S}$$

Also, the magnetic field intensity in the gap between the two solenoids must be determined. This can be done by means of a fluxmeter or even by a suitable formula, but neither fluxmeter or formula were available. However, a formula for the magnetic field intensity at a given point on the axis, outside of a single solenoid was found[1] and is

$$B = \frac{4\pi NI(10^{-7})}{2L} (\cos B - \cos A) \text{ Webers square meters}$$

where A is the angle between point p and the near end of the solenoid
B is the angle between point p and the far end of the solenoid
N is the number of turns of wire in the solenoid
I is the current in amperes through the solenoid
L is the length of the solenoid in meters

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[1]Emerson M. Pugh, and Emerson W. Pugh, Principles of Electricity and Magnetism (Reading, Massachusetts: Addison-Wesley Publishing Co., 1960), p. 245.

Since in the apparatus, there are two solenoids nearly end to end, it was assumed that since magnetic field intensities add vectorially that the equation for the magnetic field would be just twice the above equation or

$$B = \frac{4\pi NI(10^{-7})}{L} (\cos B - \cos A) \text{ Webers square meter}$$

and since one weber/square meter is equal to 10^4 gauss then

$$B = \frac{4\pi NI(10^{-3})}{L} (\cos B - \cos A) \text{ gauss}$$

J. J. Thomson used a ballistic galvanometer in determining the magnetic field intensity of his coils.[1] Thomson connected a test coil of wire to the ballistic galvanometer and placed in the center of another coil of wire, so as to be in a field of uniform magnetic intensity. The current through the second coil was reversed and the deflection A of the galvanometer noted. The magnetic field intensity at the center of the second coil can be calculated from the dimensions of the coil and the current through it. Thus one division of the galvanometer scale could be calibrated in terms of units of magnetic field intensity. Then this same test coil is placed in the region where the magnetic field is to be determined and the deflection thus noted again. From this deflection, the intensity of the

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[1]J. J. Thomson, "On Cathode Rays," Philosophy Magazine, XLIV (October, 1897), 309.

magnetic field can be found.

The above method was used to confirm the value given by the formula stated on the previous page. The test coil used consisted of 4700 turns of number 42 copper enameled wire. The second or standard coil consisted of 1200 turns of number twenty-six copper enameled wire wound on a mailing tube with 28.53 centimeters winding length. The magnetic field intensity at the center of this coil is given by

$$B = \frac{4\pi NI(10^{-3})}{L} \text{ gauss}$$

where B is the magnetic field intensity
N is the number of turns of wire
I is the current in the coil in amperes
L is the length of the coil in meters

The test coil was placed at the center of this standard coil and the deflection noted at various currents through the coil. Table I gives current readings, deflection readings and calculations of magnetic field intensity per millimeter deflection for standard coil.

The test coil was then placed in the center of the gap between the two 2400 turn solenoids. When the current was reversed in the solenoids, the galvanometer deflection was noted for various currents.

TABLE I

CURRENT READINGS, DEFLECTION READINGS AND CALCULATION OF MAGNETIC FIELD INTENSITY PER MILLIMETER DEFLECTION FOR STANDARD COIL

current reading	deflection	magnetic field per millimeter
400 ma.	25.8 mm	
400	25.8	
400	25.7	
400	25.8	
400	25.9	
400	25.9	average value
400	25.8	for 400 ma.
400	25.6	current is
400	25.8	.820 gauss/mm
400 ma.	25.8	
	ave. 25.8 mm	
300	19.1 mm	
300	19.3	
300	19.1	
300	19.6	average value
300	19.1	for 300 ma.
300	19.3	current is
300	19.6	.822 gauss/mm
300	19.6	
300	19.1	
300	19.1 mm	
	ave. 19.3 mm	
200	13.1 mm	
200	13.1	
200	12.9	
200	12.6	average value
200	12.9	for 200 ma.
200	12.6	current is
200	13.1	.820 gauss/mm
200	12.9	
200	12.9	
200	12.9 mm	
	ave. 12.9 mm	

Table II shows the galvanometer deflection from the test coil at the center of the gap for the various currents used.

TABLE II

GALVANOMETER DEFLECTION FROM THE TEST COIL AT THE CENTER OF THE GAP FOR THE VARIOUS CURRENTS USED

current reading	deflection	current reading	deflection	current reading	deflection
400 ma.	7.5 mm	300 ma.	5.8 mm	200 ma.	3.8 mm
400	7.8	300	5.7	200	3.8
400	7.7	300	5.8	200	3.8
400	7.7	300	5.8	200	4.0
400	7.7	300	5.8	200	3.8
400	7.7	300	5.8	200	3.8
400	7.6	300	5.8	200	3.5
400	7.6	300	5.8	200	3.8
400	7.8	300	5.8	200	3.8
400	7.8 mm	300	5.8 mm	200	3.8 mm
ave.	7.7 mm	ave.	5.8 mm	ave.	3.8

Table III shows the comparison between the values for the magnetic field obtained by the galvanometer and by the formula on page 2 , at the three currents listed.

TABLE III

COMPARISON BETWEEN THE TWO METHODS OF DETERMINING THE MAGNETIC FIELD

current in solenoid	magnetic field from formula	magnetic field from galvanometer
400 ma.	6.32 gauss	6.32 gauss
300 ma.	4.74 gauss	4.76 gauss
200 ma.	3.16 gauss	3.12 gauss

It is believed that the above data substantiates the assumption made in arriving at the formula on page 2 . Therefore, the equation for the magnetic field intensity on page is the one that will be used to determine the magnetic field intensity of the solenoids used in the e/m apparatus.

CHAPTER IV

METHOD OF TREATMENT OF ERRORS

Observations are taken in the process of research and from these observations certain conclusions are usually made. Since no observation or series of observations is absolutely accurate, it is desirable to check the dependability of the conclusions by a study of the errors in the research.

With a group of measurements of a given variable, the question arises as to what value has the highest probability of being correct. To answer this question the methods of statistics are used and although the proof is difficult the conclusions are rather simple. The arithmetic mean, a.m., obtained by dividing the sum of the observed values by the number of observations taken, represents the best value obtainable from a series of observations.[1]

The square root of the sum of the squares of the difference between the arithmetic mean and the individual observation, divided by the total number of observations, is called the root mean square or the standard deviation and is a

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[1]Murray R. Spiegel, Theory and Problems of Statistics (New York: Schaum Publishing Co., 1961), p. 45-46.

measure of the accuracy of the measurement.

$$\text{R.M.S. or s.d.} = \sqrt{\frac{\Sigma(x-\bar{x})^2}{N}}$$

where R.M.S. is Root Mean Square
s.d. is Standard Deviation
Σ is symbol meaning "sum of"
x is observed reading
$\bar{x}$ is the arithmetic mean
N is the total number of readings

The probable error of a measurement, with a ninety-nine percent confidence level, is given by[1]

$$\text{P.E.} = \frac{3.25 \text{ s.d.}}{\sqrt{N-1}}$$

Therefore 99% of the observed values should fall in the range $\bar{x} \pm$ P.E. This gives the limit of expected error for a single variable, but then the question arises as to how to handle the compounding of errors from several variables.

The error produced by multiplying or dividing several variables can be found by taking the square root of the sum of the squares of the percentage probable errors. The percentage probable error can be found by use of the following equation

$$\text{P.P.E.} = \frac{100 \text{ P.E.}}{\bar{x}}$$

[1] *Ibid.*, p. 189.

If one of the observed variables is raised to some power n, then its percentage probable error is multiplied by n, then squared and added to the sum of the other percentage probable errors under the radical.

The equations and methods stated above will be used in determining the final error of the experimental value of e/m. Therefore the standard deviation, probable error and percentage probable error will have to be determined for each of the variables involved in the apparatus.

CHAPTER V

STANDARDIZATION OF THE APPARATUS

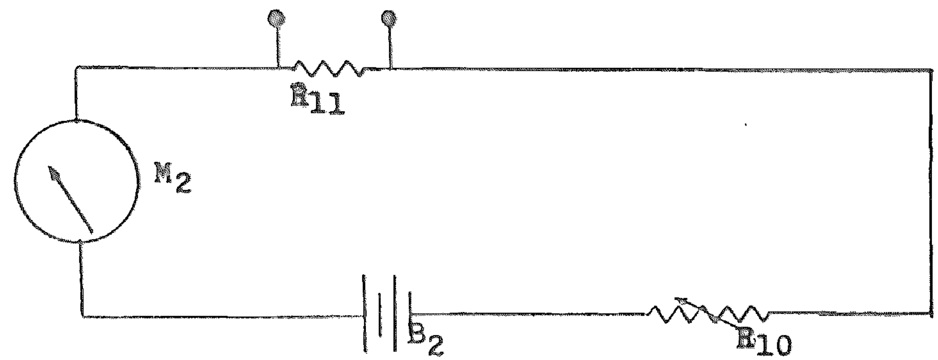
This chapter is devoted to the subject of the standardization of the various parts and variables that will affect the final value in the determination of the ratio of charge to mass of an electron. This procedure was completed by making several determinations of the dimensions of the various parts and of the values that could be expected from the meters and the standard deviation of each set of measurements.

This standardization process was performed on the following parts of the apparatus: ammeter, resistor for the standardization of the ammeter, length of the magnetic field coils, width of the gap between the coils, length of the deflection plates, distance from the center of the deflection plates to the screen, distance between the deflection plates and the voltmeter.

Ammeter. A known resistance was placed in series with the milliammeter and the voltage drop across the resistor was measured with a potentiometer. By knowing the resistance of the resistor and the voltage drop across the resistor it is possible, by use of Ohm's Law, to calculate the current through the resistor, which is the same as the current through the milliammeter. Figure 8 shows the circuit used to standardize the milliammeter.

A resistor of nichrome wire was made for the known resistance and its resistance was determined by use of a Leads and Northrup No. 4760 Wheatstone Bridge. Table IV gives the readings from the wheatstone bridge for the resistance of the nichrome resistor, the squares of the deviations, the probable error and the percentage probable error.

Next the potentiometer readings for the voltage across the known resistor were taken. Ten values were obtained for each of seven settings of the ammeter. These settings were: 400 ma., 350 ma., 300 ma., 250 ma., 200 ma., 150 ma., and 100 ma. The procedure for taking these ten values was to take one voltage reading across the resistor with the ammeter set at 400 ma., then take one reading with the ammeter set at 350 ma. and similarly with the other settings and repeating the procedure until ten voltage readings were obtained from the potentiometer for each setting of the ammeter.



M_2 = Milliammeter.

B_2 = 6 Volt Battery.

R_{10} = Variable Resistor.

R_{11} = Nichrome Resistor.

Figure 8. The Circuit Used to Standardize the Milliammeter.

TABLE IV

VALUES OF RESISTANCE, THE SQUARE OF THE DEVIATIONS, THE STANDARD DEVIATION, THE PROBABLE ERROR AND THE PERCENTAGE PROBABLE ERROR

wheatstone bridge readings	deviation squared	standard deviation, P.E. and P.P.E.
2.374 ohms	0.000×10^{-3}	
2.374	0.001	s.d. = 1.30×10^{-3}
2.375	0.001	
2.375	0.000	P.E. = 1.41×10^{-3}
2.373	0.001	
2.372	0.004	P.P.E. = 5.9×10^{-2}%
2.372	0.004	
2.372	0.004	
2.373	0.001	
2.375	0.001	
2.374 ohms average	$.017 \times 10^{-3}$ total	

Table V shows the meter settings, the potentiometer readings and the square of the deviation for each reading.

TABLE V

METER SETTING, POTENTIOMETER READING AND DEVIATION SQUARED

meter setting	potentiometer reading	deviation squared
400 ma.	0.9486 volts	0.0100×10^{-4}
"	0.9453	0.1849
"	0.9475	0.0441
"	0.9506	0.0100
"	0.9488	0.0064
"	0.9494	0.0004
"	0.9540	0.1936
"	0.9505	0.0081
"	0.9505	0.0081
"	0.9509	0.0169×10^{-4}
	average 0.9496 volts	total 0.4825×10^{-4}

TABLE V (continued)

meter setting		potentiometer reading		deviation squared
350 ma.		0.8279 volts		0.0676 x 10^{-4}
"		0.8275		0.0900
"		0.8280		0.0625
"		0.8315		0.0100
"		0.8324		0.0361
"		0.8315		0.0100
"		0.8347		0.1764
"		0.8307		0.0004
"		0.8299		0.0036
"		0.8305		0.0000
	average	0.8305 volts	total	0.4566 x 10^{-4}
300 ma.		0.7082 volts		0.1089 x 10^{-4}
"		0.7070		0.2025
"		0.7105		0.0100
"		0.7127		0.0144
"		0.7129		0.0196
"		0.7112		0.0009
"		0.7175		0.3600
"		0.7102		0.0169
"		0.7129		0.0196
"		0.7120		0.0025
	average	0.7115 volts	total	0.7553 x 10^{-4}
250 ma.		0.5892 volts		0.0225 x 10^{-4}
"		0.5897		0.0100
"		0.5906		0.0001
"		0.5914		0.0049
"		0.5906		0.0001
"		0.5908		0.0001
"		0.5918		0.0121
"		0.5908		0.0001
"		0.5910		0.0009
"		0.5913		0.0036
	average	0.5907 volts	total	0.0544 x 10^{-4}
200 ma.		0.4743 volts		0.0001 x 10^{-4}
"		0.4740		0.0004
"		0.4731		0.0121
"		0.4742		0.0000
"		0.4749		0.0049
"		0.4748		0.0036
"		0.4740		0.0004
"		0.4743		0.0001
"		0.4741		0.0001
"		0.4745		0.0009
	average	0.4742 volts	total	0.0226 x 10^{-4}

TABLE V (continued)

meter setting	potentiometer reading	deviation squared
150 ma.	0.3512 volts	0.2209×10^{-4}
"	0.3550	0.0081
"	0.3567	0.0064
"	0.3543	0.0256
"	0.3570	0.0121
"	0.3579	0.0500
"	0.3570	0.0121
"	0.3573	0.0196
"	0.3551	0.0064
"	0.3576	0.0289
	average 0.3559	total 0.3801×10^{-4}
100 ma.	0.2351 volts	0.0049×10^{-4}
"	0.2360	0.0004
"	0.2356	0.0004
"	0.2359	0.0001
"	0.2350	0.0064
"	0.2355	0.0009
"	0.2355	0.0009
"	0.2360	0.0004
"	0.2385	0.0289
"	0.2345	0.0169
	average 0.2358 volts	total 0.0602×10^{-4}

Table VI lists the standard deviation, probable error and the percentage probable error of the potentiometer readings at the various ammeter settings.

TABLE VI

STANDARD DEVIATION, PROBABLE ERROR AND PERCENTAGE PROBABLE ERROR OF POTENTIOMETER READINGS

meter setting	standard deviation	probable error	percent probable error
400 ma.	21.96×10^{-4}	23.79×10^{-4}	25.05×10^{-2}
350 ma.	21.37	23.15	27.87
300 ma.	27.48	29.77	41.84
250 ma.	7.38	8.00	13.54
200 ma.	4.75	5.15	10.86
150 ma.	19.50	21.13	59.37
100 ma.	7.76	8.41	35.67

Table VII lists the meter settings, the correct meter readings and the percentage probable error of the ammeter.

TABLE VII

METER SETTINGS, ACTUAL METER READINGS AND PERCENTAGE PROBABLE ERROR OF THE AMMETER

meter setting	actual meter reading	percent probable error
400 ma.	400 ma.	0.257%
350 ma.	350 ma.	0.285%
300 ma.	300 ma.	0.423%
250 ma.	249 ma.	0.148%
200 ma.	200 ma.	0.124%
150 ma.	150 ma.	0.597%
100 ma.	99 ma.	0.114%

Magnetic field coils. To determine the strength of the magnetic field; the length of the coil, the diameter of the coil and the width of the gap between the two coils must be known. To determine the respective values and the errors involved in their measurement, ten random measurements were taken of each of the above variables.

Table VIII gives the measured length, standard deviation and the deviation squared for the measured length of the magnetic field coil.

Table IX gives the measured diameter, deviations squared, standard deviation, probable error and percentage probable error of the diameter of the magnetic field coil.

TABLE VIII

MEASURED LENGTH, DEVIATIONS SQUARED
STANDARD DEVIATION, PROBABLE ERROR
AND PERCENTAGE PROBABLE ERROR OF
THE MAGNETIC FIELD COIL

measured length	deviation squared	standard deviation, P.E. and P.P.E.
27.60 cm.	12.1×10^{-3}	
27.58	16.9	s.d. = 1.37×10^{-1}
27.84	16.9	
27.64	4.9	
27.60	12.1	P.E. = 1.48×10^{-1}
27.51	40.0	
27.85	19.6	
27.72	0.1	P.P.E. = 0.534%
27.88	28.9	
27.90	36.1	
27.71 average	187.6×10^{-3} total	

TABLE IX

MEASURED DIAMETER, DEVIATIONS SQUARED,
STANDARD DEVIATION, PROBABLE ERROR
AND PERCENTAGE PROBABLE ERROR OF
THE MAGNETIC FIELD GOAL

measured diameter	deviation squared	standard deviation, P.E. and P.P.E.
2.46 cm	4.0×10^{-4}	
2.52	16.0	s.d. = 2.05×10^{-2}
2.50	4.0	
2.48	0.0	
2.46	4.0	P.E. = 2.22×10^{-2}
2.46	4.0	
2.49	1.0	
2.46	4.0	P.P.E. = 0.895%
2.46	4.0	
2.47	1.0	
2.48 cm average	42.0×10^{-4} total	

Table X contains the measured width of the gap between the coils, standard deviation, deviations squared, probable error and percentage probable error.

TABLE X

MEASURED GAP WIDTH, DEVIATIONS SQUARED,
STANDARD DEVIATION, PROBABLE ERROR
AND PERCENTAGE PROBABLE ERROR
OF GAP BETWEEN COILS

measured gap width	deviation squared	standard deviation, P.E. and P.P.E.
4.05 cm.	9.0×10^{-4}	
4.06	4.0	s.d. = 1.52×10^{-2}
4.07	1.0	
4.08	0.0	
4.10	4.0	P.E. = 1.65×10^{-2}
4.08	0.0	
4.09	1.0	
4.08	0.0	P.P.E. = 0.404%
4.06	4.0	
4.08	0.0	
4.08 cm. average	23.0×10^{-4}	

<u>Magnetic field intensity formula</u>. The formula for the magnetic field intensity is given by:

$$B = \frac{4\pi NI(10^{-3})}{L} (\text{Cos } B - \text{Cos } A)$$

The terms of this formula are defined in Chapter III and angle A and anble B are shown in Figure 9.

To determine the Cosines of angle A and angle B, it was necessary to compute the tangents of these angles and then use trigonometry tables to find the Cosines of the

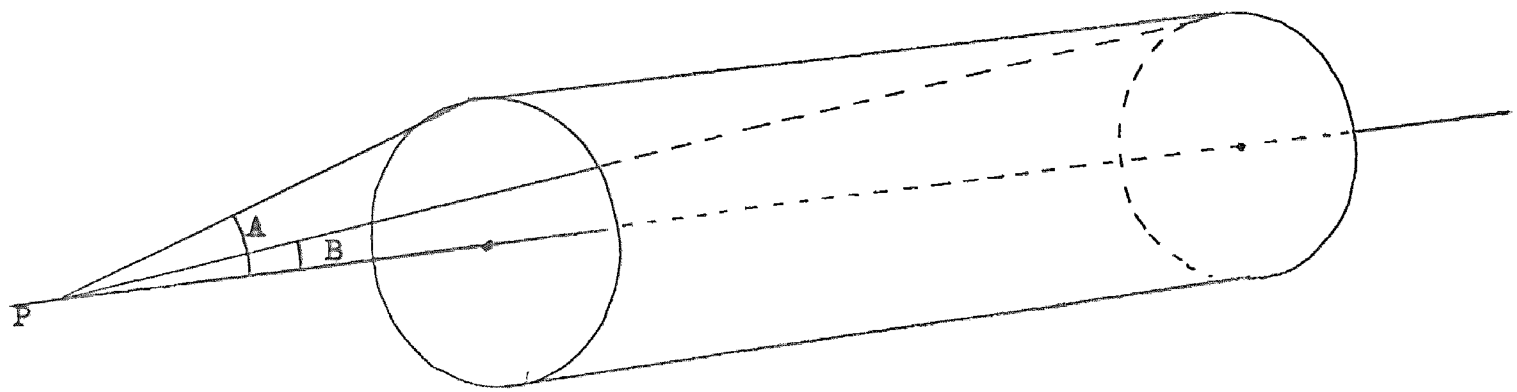


Figure 9. Diagram of Solenoid

angles. The error in the measurement of the tangent is also the error of the measurement of the cosine.

$$\text{Tan A} = \frac{1.24 \pm 0.711\%}{2.04 \pm 0.372\%}$$

$$\text{Tan A} = .6078 \pm 0.803\%$$

$$\text{Tan B} = \frac{1.24 \pm 0.711\%}{29.75 \pm 0.499\%}$$

$$\text{Tan B} = 0.04167 \pm 0.869\%$$

From the trigonometry tables:

$$\text{Cos A} = 0.8544$$

$$\text{Cos B} = 0.9991$$

Therefore

$$\text{Cos A} = 0.8544 \pm 0.803\%$$

$$\text{Cos B} = 0.9991 \pm 0.869\%$$

The value for Cos B - Cos A is $0.145 \pm 1.18\%$. This value will be used in determining the final degree of error in the measurement of e/m for electrons.

Cathode ray tube. To measure the length of the deflection plates, the distance between the plates and the distance from the center of the plates to the screen, a cathode ray tube of the same type and number as the one used was carefully broken in order not to damage any of the internal parts. After breaking the tube, it was possible to measure the plates by direct use of a set of vernier calipers and also to make measurements of the distance from the center of the plates to the screen.

Table XI contains measured plate length, deviations squared, standard deviation and percentage probable error.

TABLE XI

MEASURED PLATE LENGTH, DEVIATIONS SQUARED, STANDARD DEVIATION, PROBABLE ERROR AND PERCENTAGE PROBABLE ERROR

measured plate length	deviation squared	standard deviation P.E. and P.P.E.
1.98 cm.	4.0×10^{-4}	
2.02	4.0	s.d. = 1.64×10^{-2}
1.98	4.0	
2.00	0.0	
2.02	4.0	P.E. = 1.78×10^{-2}
1.99	1.0	
2.01	1.0	
2.01	1.0	P.P.E. = 0.890%
1.98	4.0	
1.98	4.0	
2.00 cm. average	27.0×10^{-4} total	

Table XII contains the measured distance between the plates, deviations squared, standard deviation, probable error and percentage probable error.

TABLE XII

PLATE SEPARATION, DEVIATIONS SQUARED, STANDARD DEVIATION, PROBABLE ERROR AND PERCENTAGE PROBABLE ERROR

separation of plates	deviation squared	standard deviation P.E. and P.P.E.
5.0 mm.	0.0×10^{-2}	
5.0	0.0	s.d. = 6.32×10^{-2}
5.1	1.0	
5.0	0.0	
4.9	1.0	P.E. = 6.84×10^{-2}
4.9	0.0	
5.0	0.0	
5.0	1.0	P.P.E. = 1.36%
5.0	0.0	
5.1	1.0	
5.0 mm. average	4.0×10^{-2} total	

Table XIII contains the measured values of the distance from the center of the plates to the screen, deviations squared, probable error, standard deviation and percentage probable error.

Voltmeter. The voltmeter used in the apparatus consists of a fifty microampere basic movement ammeter connected in series with a two million ohm carbon resistor. The internal resistance of the ammeter is 1940 ohms, the value being supplied by the manufacturer. The resistor is

TABLE XIII

DISTANCE FROM CENTER OF PLATES TO SCREEN, DEVIATIONS SQUARED, STANDARD DEVIATION, PROBABLE ERROR AND PERCENTAGE PROBABLE ERROR

distance from center of plates to screen	deviation squared	standard deviation, P.E. and P.P.E.
27.23 cm.	64.0×10^{-4}	
27.10	25.0	s.d. = 4.88×10^{-2}
27.10	25.0	
27.24	81.0	
27.19	16.0	P.E. = 5.29×10^{-2}
27.12	9.0	
27.16	1.0	
27.14	1.0	P.P.E. = .194%
27.11	16.0	
27.15	0.0	
27.15 am average	238.0×10^{-4}	

a ± 1% precision carbon resistor.

To successfully standardize the voltmeter, it would be necessary to accurately measure the sum of the voltage drops across the meter and the carbon resistor. Since a 1% change in the carbon resistor could change the voltage drop across it by as much as one volt, which is more than the voltage drop across the meter, it is impossible to measure both voltage drops at the same time with any accuracy with the available equipment. Thus the accuracy of the voltmeter will be taken as ± 1% of the reading obtained from it.

CHAPTER VI

INVESTIGATIVE PROCEDURE, DATA AND CALCULATIONS

Investigative Procedure. The procedure for using the apparatus to determine e/m is as follows. The switch for the magnetic field direction is set to either the up or the down position. The position of the bright spot on the screen is set at zero with no electrostatic or magnetic deflection. The magnetic field is turned on and the current adjusted to the desired setting. Then the electrostatic deflection voltage is regulated until the bright spot is moved back to the starting position. The amount of deflection due to the magnetic field, the current reading and the voltage reading are noted.

To find out if the earth's magnetic field had any effect on the value obtained from the apparatus, one set of readings was taken with the magnetic field down and one set with the magnetic field up and the results compared.

In making the determination of e/m for this research five measurements of the magnetic deflection were taken and the average value, the standard deviation, the probable error and the percentage probable error computed.

Data. Table X gives the meter settings, magnetic field direction, voltage readings, deflection measurements, and averages of the deflection values for determination of e/m.

TABLE XIV

METER SETTINGS, MAGNETIC FIELD DIRECTION, VOLTAGE READINGS, DEFLECTION MEASUREMENTS AND AVERAGES OF THE DEFLECTION MEASUREMENTS FOR DETERMINATION OF e/m

meter setting	magnetic field direction	initial voltage reading	final voltage reading	deflection voltage	deflection measurement trials (centimeters) 1	2	3	4	5	average
400	up	9.5	64.0	54.5	3.50	3.49	3.45	3.47	3.44	3.47
400	down	4.0	59.5	55.5	3.45	3.49	3.50	3.55	3.55	3.51
350	up	9.5	57.0	47.5	3.05	3.07	3.07	3.00	3.02	3.04
350	down	4.0	51.5	47.5	3.06	3.05	3.03	3.04	3.05	3.05
300	up	9.5	49.5	40.0	2.60	2.60	2.58	2.57	2.57	2.58
300	down	4.0	44.5	40.5	2.60	2.59	2.60	2.62	2.60	2.60
250	up	9.5	43.5	34.0	2.14	2.14	2.10	2.11	2.13	2.12
250	down	4.0	38.5	34.5	2.14	2.18	2.18	2.15	2.16	2.16
200	up	10.0	37.0	27.0	1.70	1.73	1.78	1.75	1.77	1.75
200	down	4.0	31.5	27.5	1.76	1.75	1.77	1.74	1.75	1.75

Table XV lists the meter settings, magnetic field directions, average value for deflection, standard deviation, probable error and percentage probable error in the magnetic deflection.

TABLE XV

METER SETTINGS, MAGNETIC FIELD DIRECTIONS, AVERAGE VALUE FOR DEFLECTION, STANDARD DEVIATION, PROBABLE ERROR AND PERCENTAGE PROBABLE ERROR IN THE MAGNETIC DEFLECTION

meter setting	magnetic field direction	average deflection (centimeters)	s.d.	P.E.	P.P.E.
400	up	3.47	0.0228	0.0370	1.07%
400	down	3.51	0.0382	0.0621	1.77%
350	up	3.04	0.0245	0.0398	1.31%
350	down	3.05	0.0110	0.0178	0.58%
300	up	2.58	0.0141	0.0229	0.89%
300	down	2.60	0.0100	0.0163	0.63%
250	up	2.12	0.0167	0.0227	1.04%
250	down	2.16	0.0161	0.0262	1.21%
200	up	1.75	0.0290	0.0471	2.69%
200	down	1.75	0.0110	0.0179	1.02%

The formula for the magnetic field intensity, given in Chapter III, page 27 is used to determine the value for the magnetic field intensity by putting in the value for the current and the length of the coil.

Table XII gives the meter settings, magnetic field intensity values and the percentage probable error in the magnetic field intensity.

TABLE XVI

METER SETTINGS, MAGNETIC FIELD INTENSITY VALUES AND THE PERCENTAGE PROBABLE ERROR IN THE MAGNETIC FIELD INTENSITY

meter setting	magnetic field intensity	percentage probable error
400	6.32 gauss	1.71%
350	5.53	1.74%
300	4.74	1.85%
250	3.95	1.69%
200	3.16	1.69%

Calculations of the ratio of the charge to mass of an electron were made by using the formulas given in chapter III. One of the variables that is needed is the value for the deflection, y, parallel to the electric field at the end of the deflection plates. This is obtained from the value of the deflection at the screen and the distance from the center of the plates to the screen.

Table XVII gives the values for y, the deflection at the screen and the percentage probable error of y.

TABLE XVII

DEFLECTION AT PLATES, DEFLECTION AT SCREEN AND PERCENTAGE PROBABLE ERROR

deflection at screen	deflection at plates	P.P.E.
3.47 cm.	0.128 cm.	1.41%
3.51	0.129	1.99%
3.04	0.112	1.60%
3.05	0.112	1.08%
2.58	0.095	1.27%
2.60	0.096	1.11%
2.12	0.078	1.38%
2.16	0.080	1.51%
1.75	0.064	2.84%
1.75	0.064	1.37%

Table XVIII contains the meter settings, magnetic field direction and e/m value with percentage error.

TABLE XVIII

METER SETTING, MAGNETIC FIELD DIRECTION AND e/m VALUE WITH PERCENTAGE ERROR

meter setting	magnetic field direction	e/m value with error
400 ma.	up	$1.74 \times 10^7 \pm 2.71\%$ e.m.u./gram
400	down	$1.79 \times 10^7 \pm 3.05\%$
350	up	$1.74 \times 10^7 \pm 2.82\%$
350	down	$1.74 \times 10^7 \pm 2.56\%$
300	up	$1.71 \times 10^7 \pm 2.66\%$
300	down	$1.74 \times 10^7 \pm 2.76\%$
250	up	$1.70 \times 10^7 \pm 2.69\%$
250	down	$1.76 \times 10^7 \pm 2.76\%$
200	up	$1.74 \times 10^7 \pm 3.66\%$
200	down	$1.77 \times 10^7 \pm 2.68\%$

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Conclusions. It was the purpose of this research to develop an apparatus that could be used feasibly in an introductory physics laboratory to determine the charge to mass ratio of an electron and also could be used to demonstrate the effects of electric and magnetic fields on an electron beam.

The apparatus was built so that the spot on the screen could be deflected left or right by the same control and also so that the magnetic field could be directed up or down as directed. It was found that the placement of the magnetic coils was very critical. The coils are to be placed perpendicular to and directly over the deflecting plates. A movement of the magnetic coil by as little as two millimeters could effect the final value of e/m by as much as five per cent.

The power supply proved to be adequate for this apparatus even though the rectifier tube was working about 300 volts over the recommended plate to cathode voltage.

The values obtained for e/m were within 3.5 percent of the accepted value of 1.76×10^7 e.m.u./ gram. As mentioned previously, the effect of the earth's magnetic field on the value obtained was investigated. One set of readings were taken with various current settings and with the magnetic field direction down and another set of readings with the magnetic field up. When the results were compared, it was found that with the magnetic field down, the value for e/m was nearly always larger than with the magnetic field up. However, the difference was only about two per cent, which is less than the error of the apparatus. Its consistency of sign, however, suggests its reality; it might be a result of the earth's magnetic field. It was noticed that when readings were being taken with the magnetic field down, the bright spot would spread out as much as eight millimeters, therefore making it difficult to determine when the spot was back at the original starting point. This was not noticed when the magnetic field was up.

As well as being able to determine e/m, with about 3.5 percent error, this apparatus is able to demonstrate electric and magnetic deflections of an electron beam. The tube has two sets of deflection plates which can produce deflection in all four directions. It is also possible to measure the electrostatic voltage producing the deflection in all of the directions. By use of the magnetic field coils or by use of external magnets, it is possible to deflect the electron beam by magnetic fields.

The velocity of the electrons can be measured when the magnetic and electrostatic forces are equal, thus demonstrating the principle of a velocity selector.

The apparatus actually performed well and is capable of being used in a physics laboratory as it is.

Recommendations. A filter in the power supply that would cut the ripple of the current to a minimum would be an improvement to the apparatus. With the present power supply the ripple is small but this could be improved by use of larger capitance in the filter circuit.

Although it was possible to deflect the electron beam both to the left and right with the aid of a switch, it might be better to design a way to eliminate the switch. One way to do this would be to build a power supply that would be capable of producing both a positive and negative voltage. By connecting a negative voltage to the point where the deflection controls are grounded, it should be possible to move the beam across the face of the screen without the aid of a switch.

If a fluxmeter were available, it would be desirable to measure the magnetic field intensity with it. Other types of magnetic coils could be used if a satisfactory method of measuring the magnetic field intensity were available.

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